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A SHALLOW-CAVITY UHF CROSSED-SLOT ANTENNA

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ABSTRACT

The shallow-cavity crossed-slot antenna is a UHF radiator designed primarily for use on a high-speed aircraft operating as the airborne terminal in a satellite-to-air communications link. The requirements, design analysis and performance characteristics are described. The antenna's shallow profile makes it attractive either as a "paste-on" or flush-mounted type radiator. Near-hemispherical radiation coverage is provided.

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I. INTRODUCTION

Within the last 5 years we have witnessed the evolution of satellite communications networks from the design and development stage to actual working systems. One of the major accomplishments realized in a system utilizing a satellite is the establishment of reliable communications for aircraft far removed from ground terminals. This introduction of operational satellites stressed the need for a family of antennas, both ground-based and airborne, designed primarily for use with this new mode of communications. This report describes a device which has both electrical and mechanical characteristics favorable to the airborne application.

A high-speed aircraft with a constantly changing look angle to the satellite dictates:

- (a) A mechanical configuration which will not present appreciable drag.
- (b) An installation requiring no elaborate structural modifications to the aircraft.
- (c) Electrical characteristics to insure continuous communications. This requires a device which provides a full upper hemisphere of coverage, is circularly polarized, and can handle the required transmitter power.

It can be shown* that although a full hemisphere of coverage is desired, if not obtainable, a preference must be made to insure coverage at the lower look angles. Figure 1 indicates the percentage of available time a satellite is seen in certain elevation angles as a function of the aircraft's geographical latitude. The available time is the horizon-to-horizon drift of a single near-synchronous satellite. The insertion into orbit of more satellites would allow the aircraft at the equator a choice of the most suitable look angle where more than one satellite might be visible. However, an aircraft moving to higher latitudes finds a progressive restriction on its available look angles to the point where only the lower elevation angles are usable.

With this in mind, an investigation was initiated to evaluate various radiators which were then being actively used in similar applications, or, had been developed for other purposes and looked attractive as a possible solution to the problem.

In each case, radiation nulls were present over certain sectors of the hemisphere. Some of those antennas tested were responsive to circular polarization over most of the hemisphere but had very poor coverage at or near the horizon. This type of radiator is referred to as an axial-mode antenna with maximum radiation along the antenna axis. Crossed dipoles over a ground plane would fit in this category. A normal-mode antenna has a null along its axis and

*M. H. Simane, "Distribution of Look Angles to a Near-Synchronous Satellite," Technical Note 1965-47, Lincoln Laboratory, M. I. T. (8 September 1965).

peaks in a plane normal to this axis. The Loop-Vee antenna fits this description as does a simple monopole or blade antenna. The former is responsive to circular polarization while the latter is strictly a linearly polarized device. Both antennas have an overhead null which is deep and broad enough to be undesirable. The sectors of poor coverage for these two types of antenna are indicated in Fig. 1.

The crossed dipole fails to meet the requirements both mechanically and electrically. The antenna protrudes above the fuselage approximately a quarter wavelength, which at UHF frequencies can cause substantial drag unless an elaborate fairing is provided. Electrically, poor radiation is apparent at and near the horizon. An alternative to this is a system utilizing two complimentary antennas (i.e., crossed dipoles for overhead coverage and a blade for low-angle coverage), but this requires switching and because there would be excessive coupling between them, the antennas must be separated physically. If they are not separated, an extremely narrow bandwidth can be expected. The total drag realized with this configuration would be the sum of the individual drags.

The development of cross slots, packaged for an airborne installation, was deemed necessary after completing the evaluation of existing radiators. Slots, if flush mounted, require no radiating element above the fuselage, thus precluding any drag problem. However, because of the slot length required at UHF frequencies, there could exist a structural problem if the slots were cut in the aircraft fuselage.

Radiation characteristics of slots cut in a flat ground plane are well known; changes in these characteristics when the slots are located on the fuselage of a large aircraft are not as well defined. Therefore, there were two main phases to the development program. First, and of prime importance, was the measurement and cataloging of the various characteristics with the slots mounted in their prospective environments. The second consideration was to find a way to prevent any structural problems on the aircraft.

II. ANTENNA DEVELOPMENT

A. General

Because we are concerned with coverage in the upper hemisphere and the proposed antenna was to be a non-switching system, a single unit had to be located on the top center line of the aircraft. Only the fore and aft position was left as a variable to be determined after a radiation pattern study. Possible conflict with existing radiators also had to be considered.

A theoretical study was conducted to determine the coverage expected from two orthogonal slots cut in a long cylinder. This was done by combining, with a quadrature phase shift, the computer outputs of axial and circumferential slot field pattern programs.

The basic pattern structures, compared with the simple flat ground-plane cases are shown in Fig. 2. Providing the amplitudes of E_θ and E_ϕ are equal and a relative 90° phase shift is inserted, there will result an antenna responsive to circular polarization at the zenith. At the four cardinal points on the horizon, however, there is a contribution of only one of the slots (the other nulls along its longitudinal axis) resulting in a vertically polarized signal. In between these points, again on the horizon, the maximum gain drops slightly but the signal tends to be more responsive to a circularly polarized signal.

B. Scale-Model Antenna

To confirm these computed results, a 1/25-scale-model KC-135 was purchased. The model consisted of a fiberglass shell coated with molten copper, with access doors to allow the installation of antennas at strategic locations on the fuselage. A scale-model crossed-slot antenna was built and located on the model aircraft. The model, being measured in a low-reflection test chamber, is illustrated in Fig. 3. The airplane model coordinate system is shown in Fig. 4 and the radiation patterns and gain measurements realized in this phase of the development are presented in Figs. 5(a) through 5(l). Results compared very favorably with the computed patterns. Figures 5(a) through 5(d) and 5(e) through 5(h) indicate the response realized at the receive and transmit frequencies, respectively. Figures 5(i) through 5(k) show the results of allowing the slots to become too long. Although the principal plane patterns are acceptable, coverage on the horizon is not omni-directional.

The use of a spinning linearly polarized transmitting antenna provides for the recording of the antenna's response to all linear polarizations. The resulting envelope is seen in these patterns as well as the vertical and horizontal polarization components. The expected circular polarization overhead and almost pure linear vertical polarizations at the horizon are evident.

Scale-model measurements were made with the antenna located in two positions on the fuselage. One position was well forward on the fuselage (Station 470) and the other in line with the trailing edge wing root (Station 1010). A comparison can be made between Figs. 5(e) and 5(l). The scalloping effect on the transverse pattern taken while in the rear location (Fig. 5(l)) is caused by reflections from the wings and motor housing. It does not show up in the forward location transverse pattern but does appear on a pattern whose plane of reference cuts through the wings. Because of the swept-back wings there are larger azimuth sectors in which wing interference can be expected when the antenna is located in an aft position than when located forward (Fig. 6). The interference caused by the vertical stabilizer is also more apparent when the antenna is located in the aft position. Therefore, if a choice of location is available there is some advantage in having the antenna forward of the wings.

Gain was measured at the zenith and then calculated at various elevation angles taking into consideration polarization mismatch (Table I). The gain on the horizon, which as mentioned

TABLE I
CROSSED-SLOT ANTENNA GAIN

Elevation Angle θ (deg)	GAIN (db)		
	Slot Length (λ)		
	0.78	0.88	1.0
90 (zenith)	4.3*	5.0*	6.0*
45†	+2.5	+2.5	+2.0
0†	-1.5	-2.0	-4.0
* Measured gain. All values are relative to circular polarized isotropic. † Calculated from zenith gain taking into consideration polarization mismatch loss. Values are average through 360° azimuth rotation.			

before is of prime interest, was found to average about -2 dB relative to a circularly polarized isotropic source. Degradation of this low-angle coverage (an increase in antenna directivity) results only if the slot length is allowed to exceed 0.9 wavelength.

A comparison of gain relative to a circularly polarized isotropic source is made (Figs. 7 and 8) between the crossed-slot antenna and a simple blade or monopole antenna.

C. Full-Scale Model

Concurrent with this test program an investigation was initiated to insure against a possible structural problem. It was correctly assumed that a structure protruding no more than 3 inches into the slip stream would not appreciably degrade the performance of a KC-135-type aircraft. Therefore, although flush mounting is necessary for higher-speed aircraft, it was decided a "paste-on" type of antenna would be designed for this phase of development and test.

For hemispherical coverage a simple slot must be enclosed on one side by a box or cavity. If this container is of such size that zero susceptance is shunted across the slot terminals, the slot impedance is doubled.* Usually a simple short-circuited waveguide section approximately a quarter-guide wavelength long is used. Its actual dimension is determined by the guide wavelength which is in turn determined by the wide dimension of the guide. If the guide is allowed to run in a plane normal to the slot, a protrusion of approximately one foot into the fuselage would be required [Fig. 9(a)].

Septating the waveguide in the H-plane, as in Fig. 9(b), has little effect on the admittance of the guide. So too, the bending of these two half-height guides into a plane parallel with the slots, as shown in Figs. 9(c) and (d), has little effect on the slot antenna impedance. Now the undesirable quarter-wave dimension is placed in a plane without unreasonable dimensional limitations. Instead, the guide height, which is not as critical, becomes the slip-stream protrusion or, in flush mounting, the amount of fuselage penetration. Because two orthogonal slots are used, a square cavity is required with a subsequent trade-off on guide width and length to determine the most appropriate side-wall dimension. In all cases the slots were cut on the diagonals to get maximum slot length out of the area available.

A number of cavities were fabricated and a 2-wavelength square ground plane with a 6-foot radius of curvature was constructed. The first unit was only 18 inches square and $1\frac{1}{2}$ inches deep. It was found to be impractical. The maximum slot length possible on this size cavity was too short and the dielectric loading needed in the cavity increased the weight substantially. This unit had a natural resonance, without dielectric loading, at a frequency where the slot length was 1.1 wavelengths and the distance L (Fig. 9) was $0.287\lambda_g$. This compares favorably with the theory on a single slot with a short-circuited waveguide section attached to the ground plane.*

The second unit was 27 inches square and $1\frac{1}{2}$ inches deep and had a resonant frequency where the slot was 1.13 wavelengths long and the distance L was $0.330\lambda_g$. The discrepancy in the L dimension indicated that the waveguide height (cavity volume) had some effect on resonance. Because the bandwidth was limited, the feed structure was changed from that indicated in Fig. 10(a) to that in Fig. 10(b). The impedance was measured at the input to a well-matched 180° hybrid. Equal length cables were then used to feed diagonal feed points while the unused ports were

* J.D. Kraus, Antennas (McGraw-Hill, New York, 1950).

terminated in matched loads. The slot dimensions were kept constant and the height of the 27-inch cavity was varied. Figure 11 indicates the effect on resonant frequency as the height is varied.

Because this unit was still too small for the desired frequency band, a cavity 35 inches square and 2 inches deep was constructed. Two other modifications were made at this time. First, the cavity, which had been made flat for ease of construction, was curved to the same 6-foot radius as the ground plane, thus making it compatible to the fuselage to be used, and second, the impedance was measured directly at the individual feed points by using two slotted lines in parallel. The 180° phase shift needed between diagonal feed points is made before the slotted lines. By placing equal length slotted sections in each of the input lines, this phase shift is maintained and the impedance is referenced directly to the antenna terminals.

The impedance realized at an individual input terminal is shown in Fig. 12(a). The slots were 0.78λ long at the receive frequency and 0.88λ long at the transmit frequency. An open-circuited stub placed 3 inches back from the input resulted in the impedance shown in Fig. 12(b). Because of the relatively narrow bandwidth involved, the 180° phase shift necessary between diagonal inputs was accomplished in line lengths rather than a hybrid. The impedance resulting when these two ports are combined is shown in Fig. 12(c). The two orthogonal inputs are then combined using line lengths sufficient to give a 90° phase differential. The input VSWR was 1.6:1 at the receive frequency and 1.34:1 at the transmit frequencies. A 20 percent bandwidth where the input VSWR was under 1.70:1 was also realized. Overhead axial ratios of approximately 3 dB were obtained at the two frequencies of interest.

D. Feed Networks

Two avenues of approach were possible in designing the feed structure for the antenna. The first, an all-coaxial line system, requires four pressurized feed-through connectors and four short cables to make the connection at installation. The matching and combining circuits could be located in the cabin. This system is somewhat space consuming, but has the advantage of being accessible. The second, a stripline network nested below the cavity, is compact and requires only a single feed-through connection, but results in a loss of accessibility. The latter approach was taken. The stripline is 1/4-inch rexolite with 2-mil thick copper conductors. A type "N" input jack is used. A pressurization box is fabricated in the skin directly under this input to house the feed-through connector and short cable which is necessary at installation.

E. Radome

The protective radome is fibreglass with an anti-erosion type outer coating. The fibreglass is 1/16-inch thick over the aperture and has a slight teardrop shape, more for aesthetic than aerodynamic purposes. The antenna is first attached to appropriate fuselage stringers with pressure-seal fasteners. The radome is then also attached through the fuselage to stringers. An outline drawing of antenna and radome is shown in Fig. 13 and the flight model of the antenna is shown in Fig. 14.

F. Conclusion

A low-silhouette crossed-slot antenna has been developed for use as an airborne terminal. It is used to communicate with a near-synchronous satellite and operates in the UHF band.

A study of existing antennas conducted prior to the crossed-slot development, indicated a definite need for a device which would more adequately fill the requirement for a full hemisphere of coverage. The crossed-slot antenna does this. The antenna is of conventional design except for its shallow cavity which reduces both aerodynamic and structural problems to a minimum. The radiation field of the antenna is right-hand circularly polarized in the zenith direction. Its polarization changes to linear vertical near the horizon. The unit is an excellent radiator for use on large, high-speed aircraft.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance and guidance of Mr. L. J. Ricardi during this program and Mr. W. E. Morrow, Jr. for the original concept of a "paste-on" type antenna. Mr. Albert Sanderson, of Group 71, was responsible for the mechanical design and his constant cooperation was appreciated.

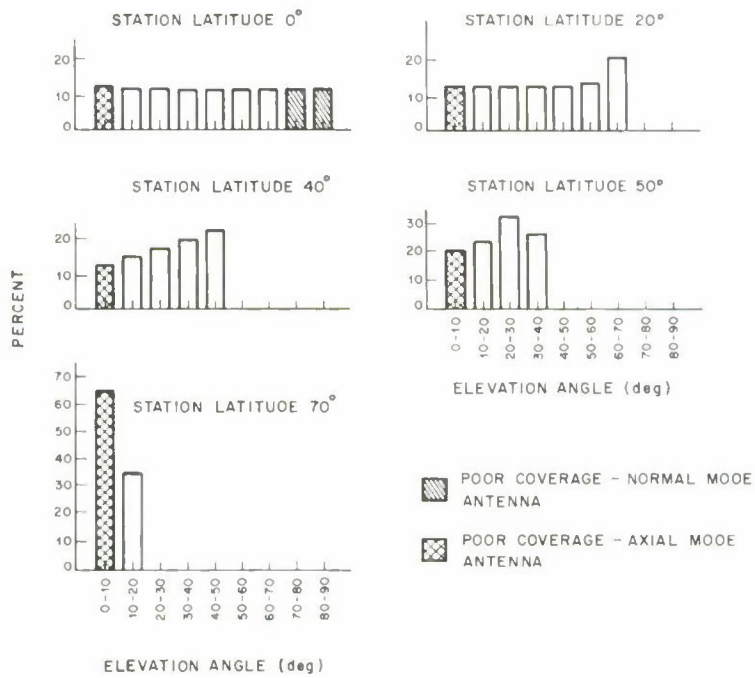


Fig. 1. Percent of available time of satellite in near-synchronous orbit is seen as a function of elevation angle and station latitude.

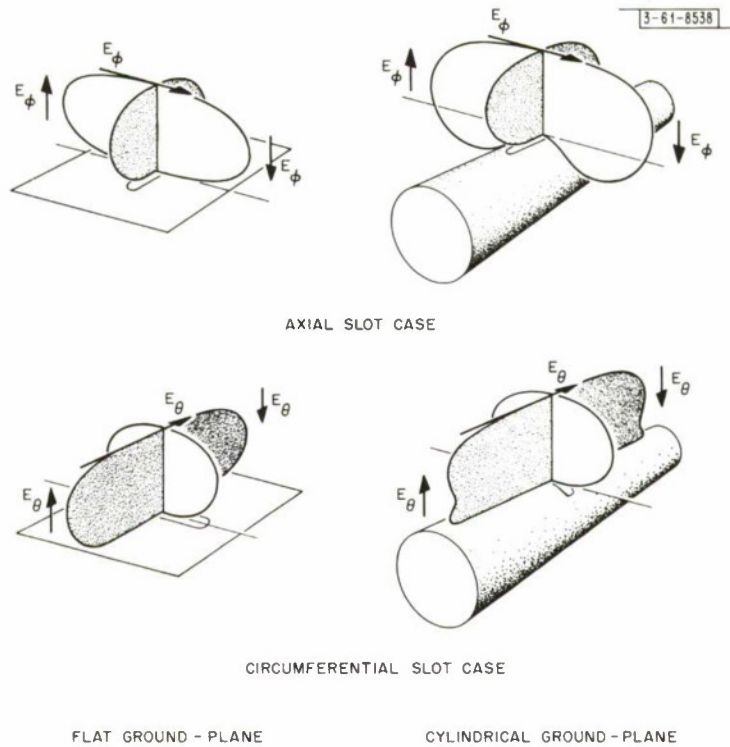


Fig. 2. Principal plane pattern structure and polarization.



Fig. 3. KC-135 aircraft and antenna (1/25-scale model) under test.

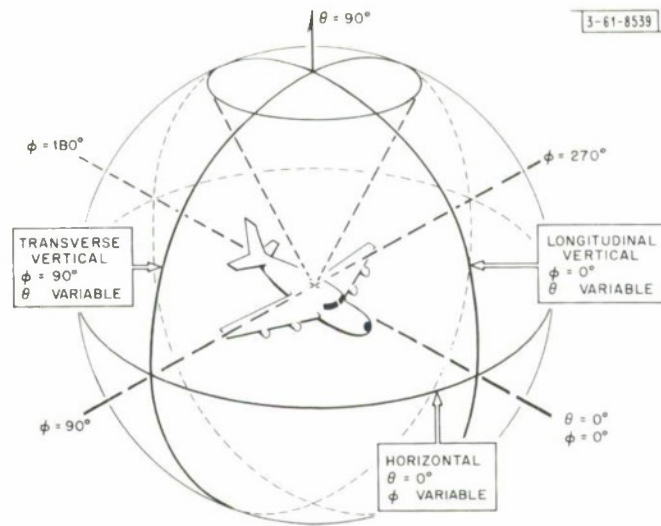
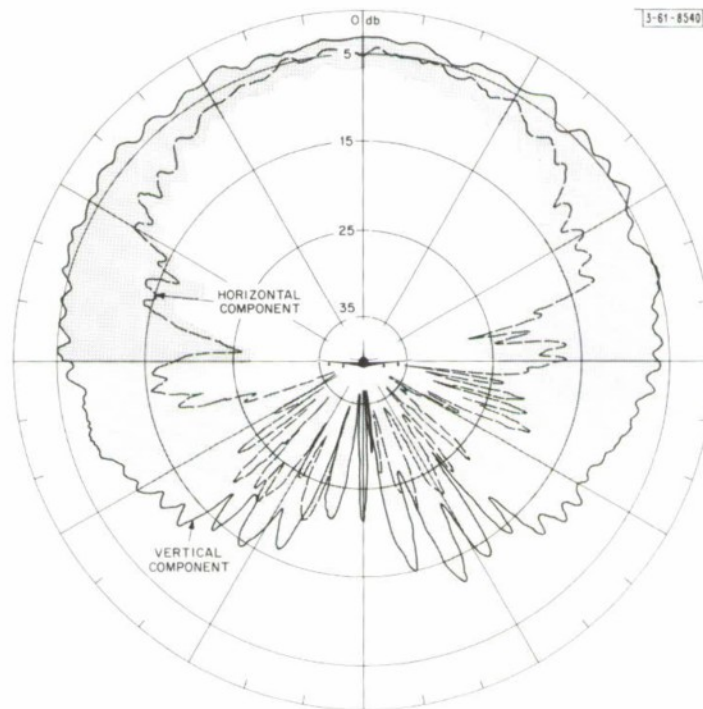
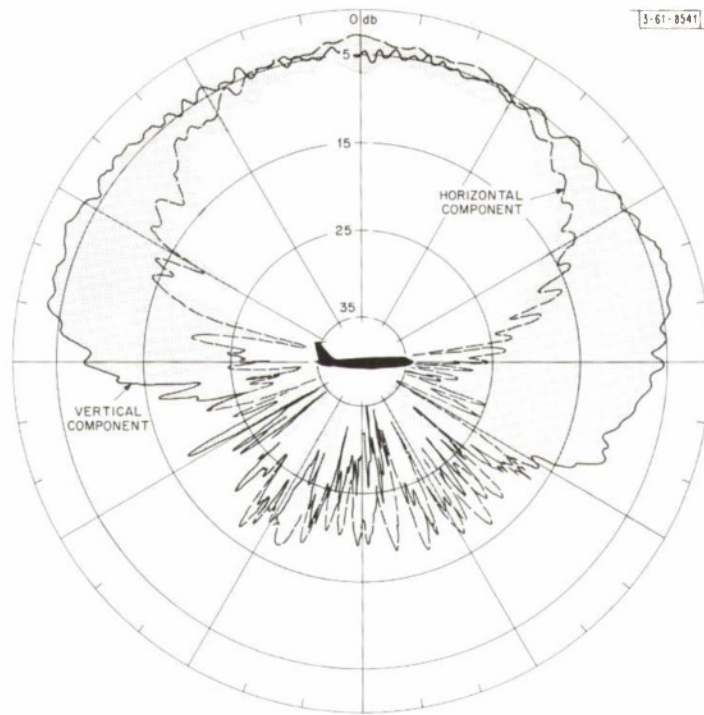


Fig. 4. Airplane model coordinate system.

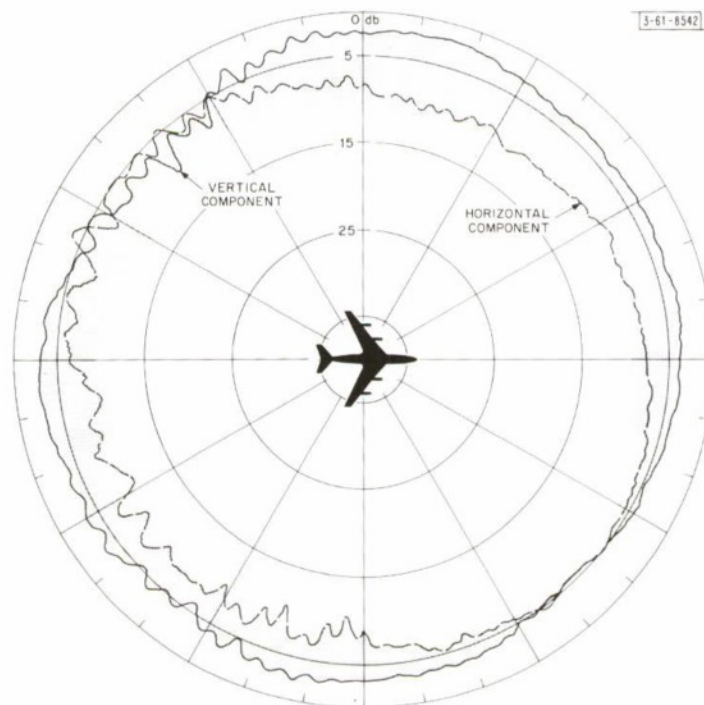


(a) Antenna location: Station 470; slot length: 0.78λ ; transverse vertical.

Fig. 5. Antenna radiation patterns — 1/25-scale-model measurements.

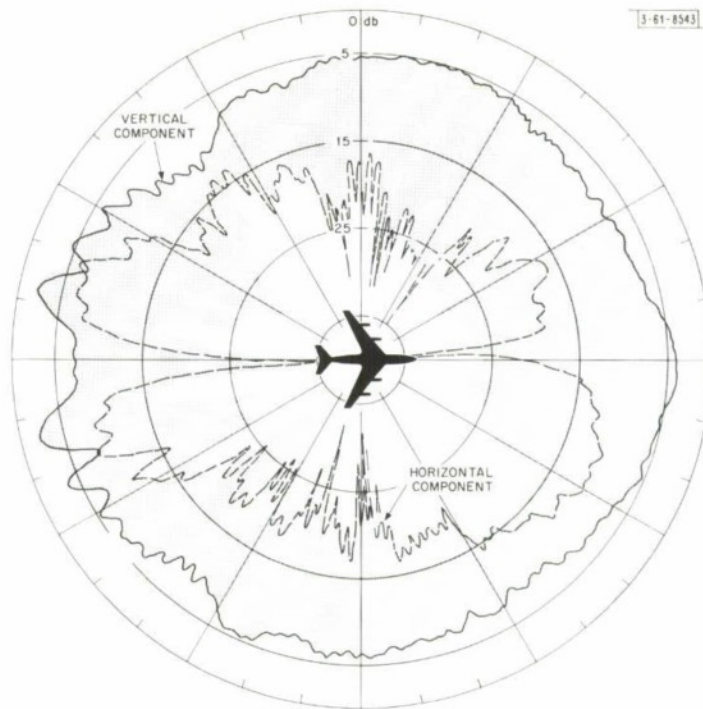


(b) Antenna location: Station 470; slot length: 0.78λ ; longitudinal vertical.

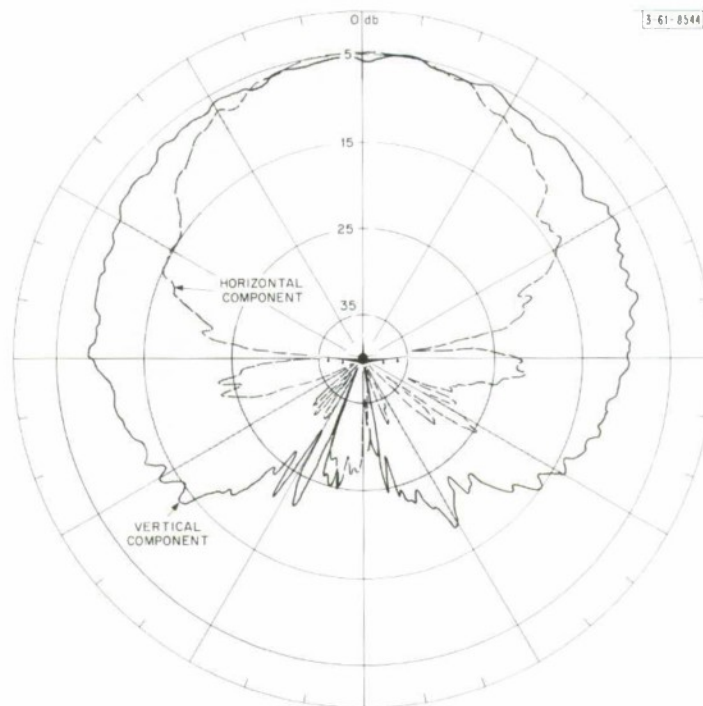


(c) Antenna location: Station 470; slot length: 0.78λ ; canical cut $\theta = 45^\circ$.

Fig. 5. Continued.

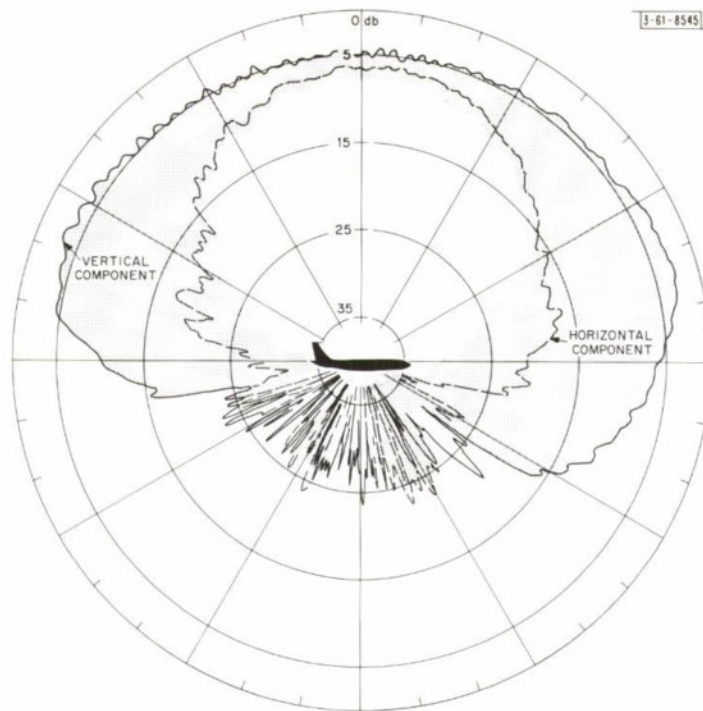


(d) Antenna location: Station 470; slot length: 0.78λ ; horizontal plane.

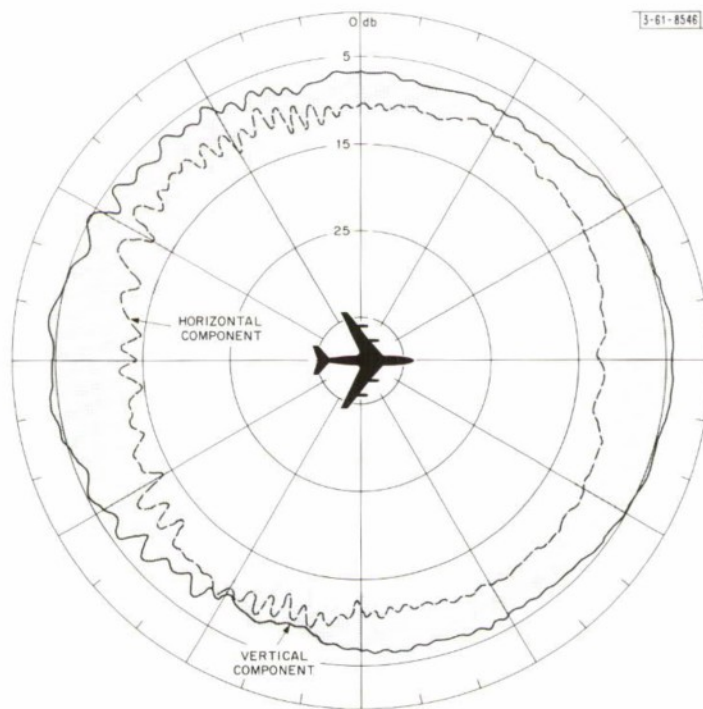


(e) Antenna location: Station 470; slot length: 0.88λ ; transverse vertical.

Fig. 5. Continued.

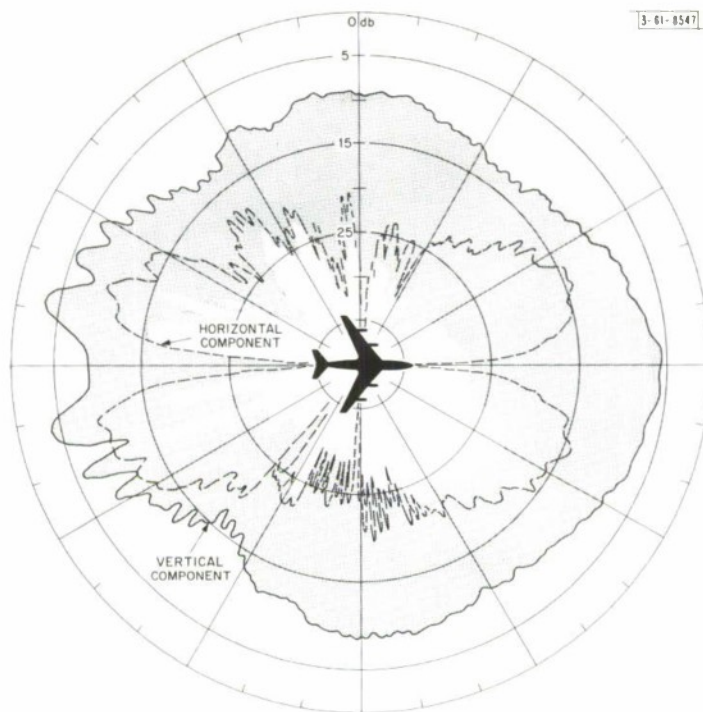


(f) Antenna location: Station 470; slot length: 0.88λ ; longitudinal vertical.

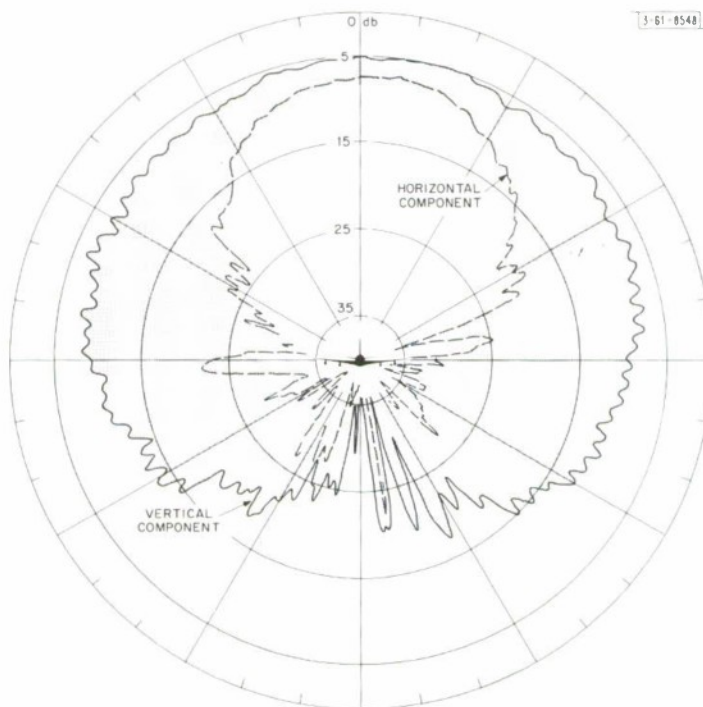


(g) Antenna location: Station 470; slot length: 0.88λ ; conical cut $\theta = 45^\circ$.

Fig. 5. Continued.

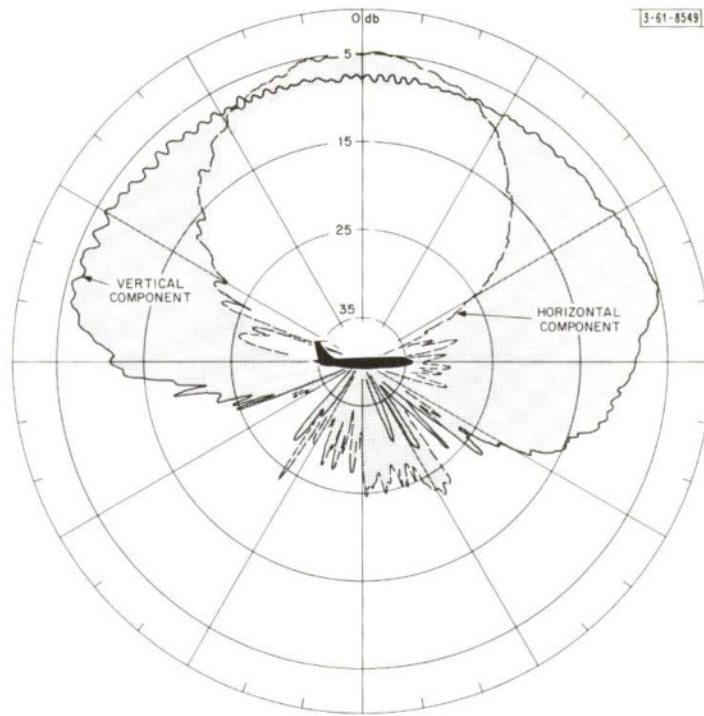


(h) Antenna location: Station 470; slot length: 0.88λ ; horizontal plane.

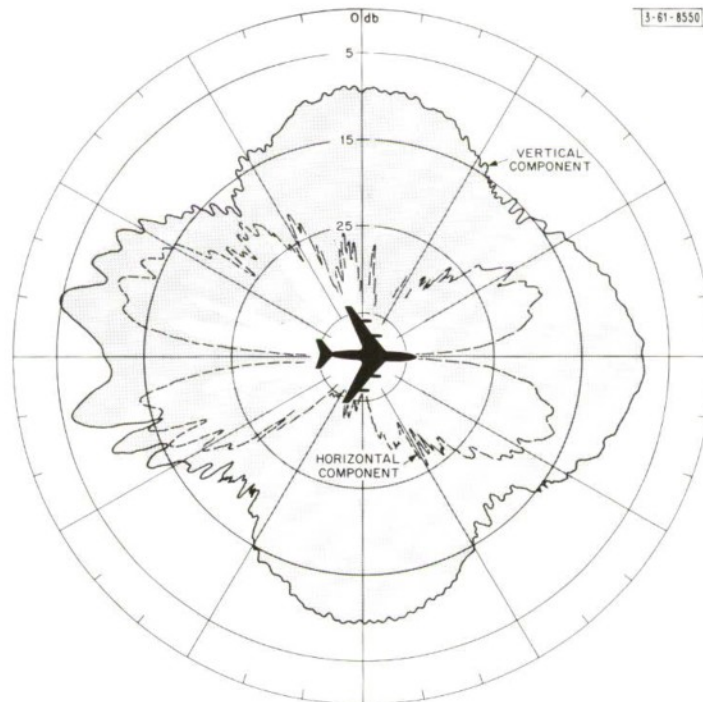


(i) Antenna location: Station 470; slot length: 1.0λ ; transverse vertical.

Fig. 5. Continued.

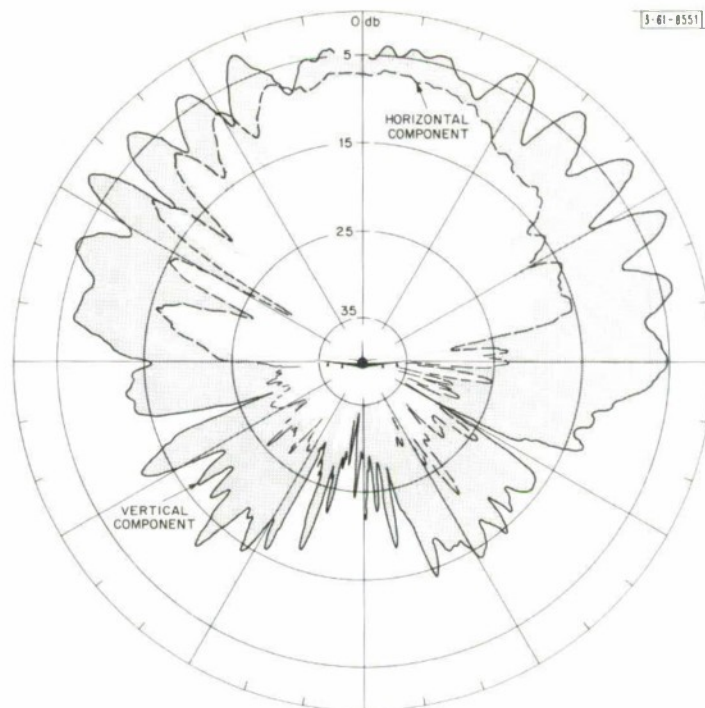


(j) Antenna location: Station 470; slat length: 1.0λ ; longitudinal vertical.



(k) Antenna location: Station 470; slat length: 1.0λ ; horizontal plane.

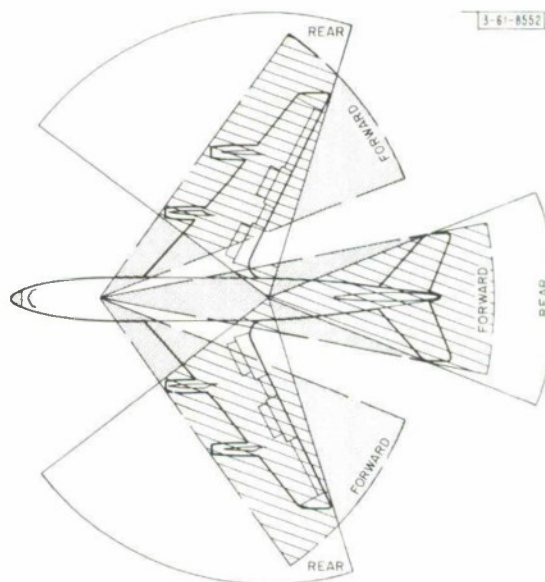
Fig. 5. Continued.



(l) Antenna location: Station 1010; slot length: 0.88λ ; transverse vertical.

Fig. 5. Continued.

Fig. 6. Sectors of possible reflection as a function of antenna location.



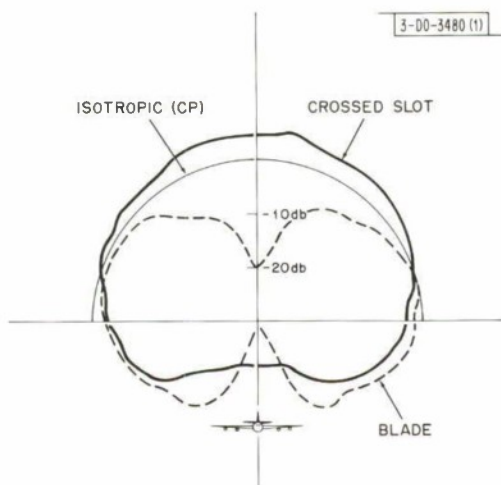


Fig. 7. Gain comparison, transverse vertical plane.

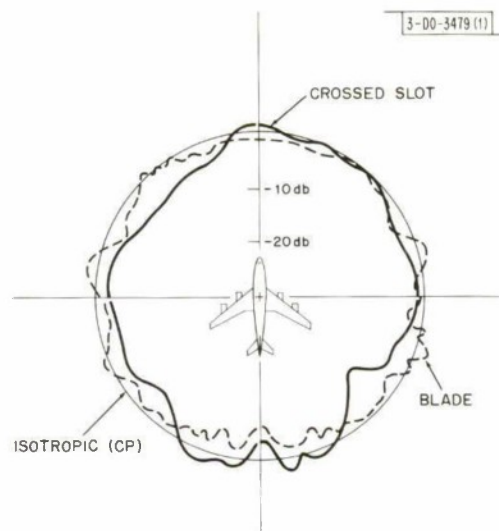


Fig. 8. Gain comparison, horizontal plane.

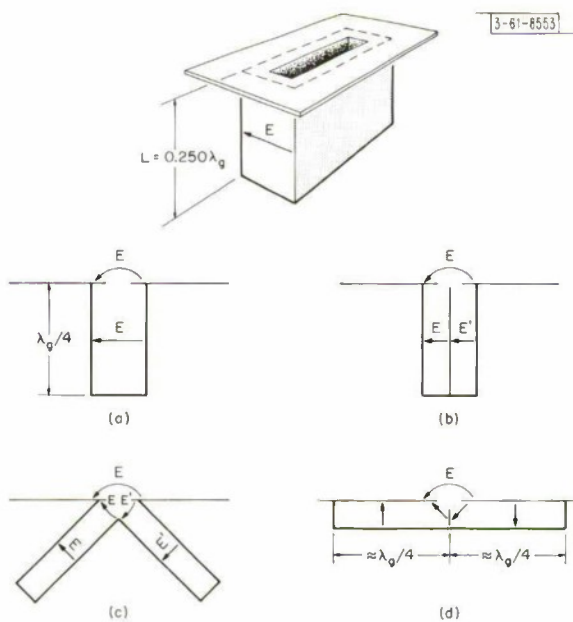


Fig. 9. Shallow cavity development.

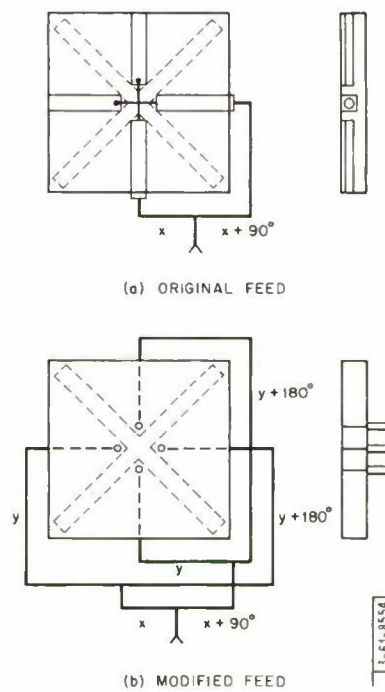


Fig. 10. Feed configurations.

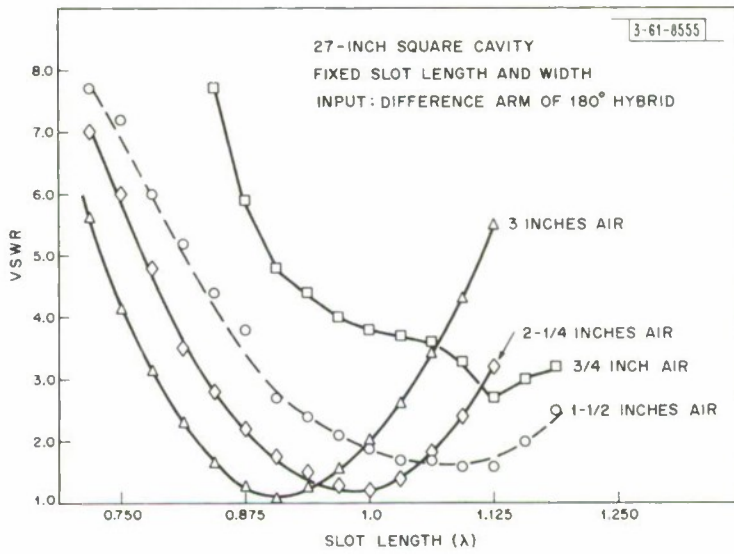


Fig. 11. VSWR vs cavity height.

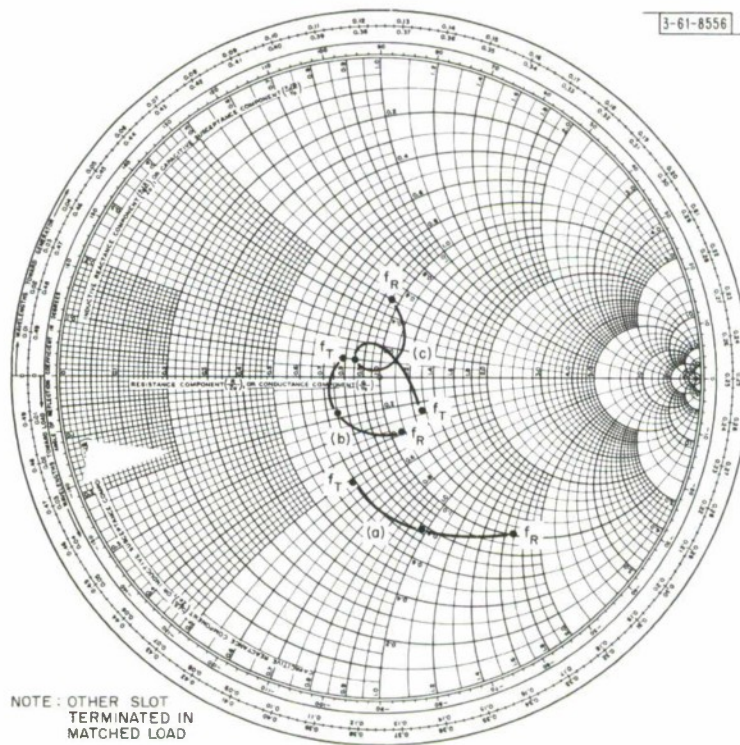


Fig. 12. Impedance curves of single slot.

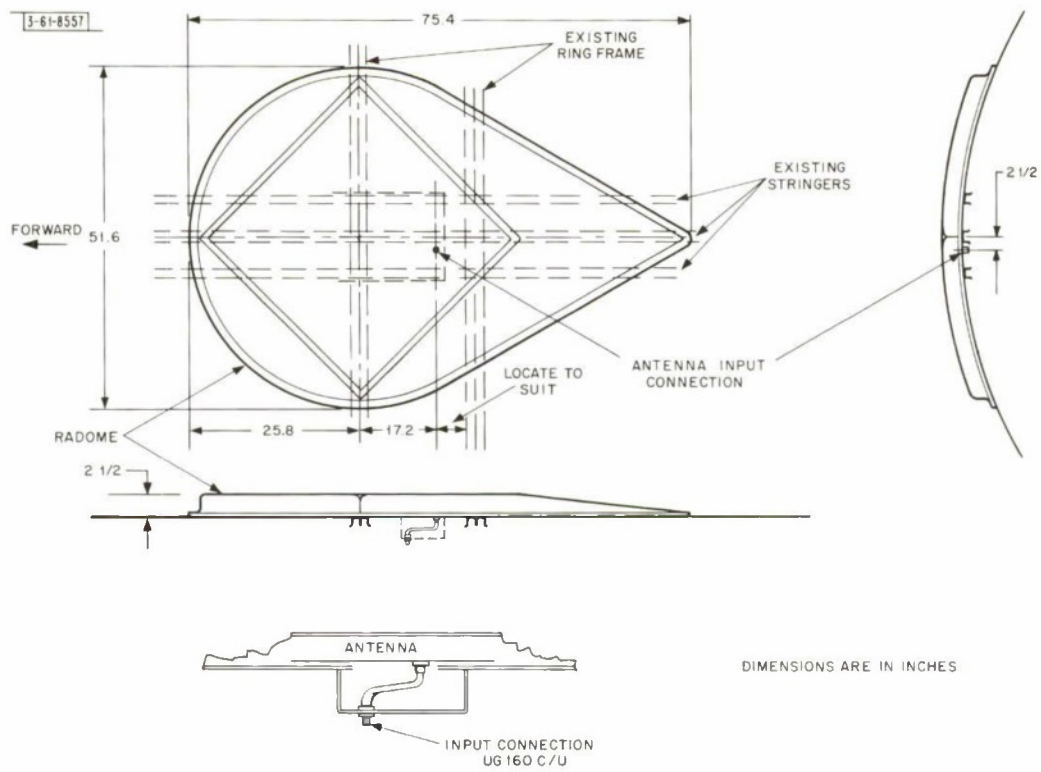


Fig. 13. Installation drawing: antenna and radome.

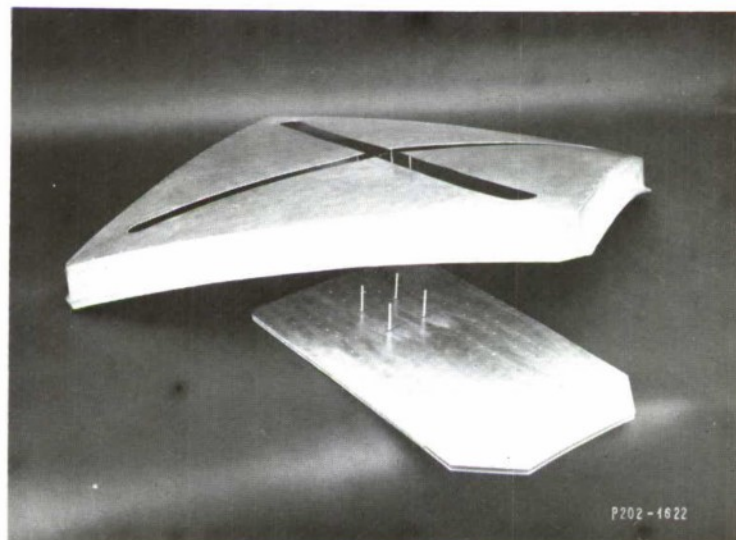


Fig. 14. Flight model antenna and feed network.

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